

# Asymmetric Dark Matter in the Shear-dominated Universe

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## Abstract

We explore the relic abundance of asymmetric Dark Matter in shear-dominated universe in which it is assumed the universe is expanded anisotropically. The modified expansion rate leaves its imprint on the relic density of asymmetric Dark Matter particles if the asymmetric Dark Matter particles are decoupled in shear dominated era. We found the relic abundances for particle and anti-particle are increased. The particle and anti-particle abundances are almost in the same amount for the larger value of the shear factor  $x_e$  which makes the indirect detection possible for asymmetric Dark Matter. We use the present day Dark Matter density from the observation to find the constraints on the parameter space in this model.

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# 1 Introduction

In addition to the Wilkinson Microwave Anisotropy Probe (WMAP) data [1], the Planck mission provided the value of the Dark Matter relic density with high precision recently [2]. Planck 2015 data gives the present cold Dark Matter relic density as

$$\Omega_{\text{DM}}h^2 = 0.1199 \pm 0.0022, \quad (1)$$

where  $h = 0.673 \pm 0.098$  is the present Hubble expansion rate in units of  $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [2].

Although there are strong evidences for the existence of Dark Matter, the nature of the Dark Matter is still not known. The usual assumption is that the neutral, long-lived or stable Weakly Interacting Massive Particles (WIMPs) are the best motivated candidates for Dark Matter. Neutralino is one example which is appeared in supersymmetry and it is Majorana particle for which its particle and anti-particle are the same. However, there are other possibilities that the Dark Matter can be asymmetric which means the particles and antiparticles are distinct from each other if the particles are fermionic [3, 4].

The relic density of asymmetric Dark Matter in the standard cosmological scenarios and non-standard cosmological scenarios like quintessence, scalar-tensor and brane world cosmological scenarios are discussed in [5, 6, 7, 8, 9, 10]. In nonstandard cosmological scenarios, the Hubble expansion rate is changed comparing to the standard cosmological scenario. If the asymmetric Dark Matter particles decay during the era in which the expansion rate is changed, both the Dark Matter particle and anti-particle abundance are affected by the modification.

The particle and anti-particle abundances are determined by solving the Boltzmann equations which are the evolution equations of the particles and anti-particles in the expanding universe. Several nonstandard cosmological models [7, 8, 9, 10] discussed the effect of the modified expansion rate on the relic density of asymmetric Dark Matter. The characteristic of the nonstandard cosmological models which are discussed in [7, 8, 9, 10] is the increase of the particle and anti-particle abundance due to the increased Hubble expansion rate. In nonstandard cosmological scenarios, for appropriate annihilation cross section, the deviation of the abundance between the particle and anti-particle are not large. For asymmetric Dark Matter, in the beginning we assume there are more particles than the anti-particles; in the end the anti-particles are completely annihilated away with the particles and there are no anti-particles left. This makes the indirect detection is impossible for asymmetric Dark Matter in the standard cosmological scenarios. However, it is changed for non-standard cosmological scenarios. The increased annihilation rate for particle and anti-particle provides us the possibility that the that the asymmetric Dark Matter can be detected indirectly.

One of the interesting nonstandard cosmological model is the Bianchi type I model in which

it is assumed the expansion of the universe is not isotropic. In this model the effects of the anisotropy on the expansion rate of the universe is quantified by an anisotropy–energy density which decreases as  $R^{-6}$  [11, 12, 13]. In [14, 15], the authors investigated the relic abundance of Dark Matter in Bianchi I cosmological model. In this paper we extend the discussion of [14, 15] to the asymmetric Dark Matter case. We investigated how the abundance of asymmetric Dark Matter particles can be affected if the asymmetric Dark Matter particles are decayed in shear–dominated universe. We discuss in detail the relic density of asymmetric Dark Matter in shear–dominated universe and then use the present Dark Matter density from the observation to find the constraints on the parameter space in shear-dominated model.

The arrangement of the paper is following. In section 2, we review the shear–dominated universe. The asymmetric Dark Matter relic density is discussed both in numeric and analytic way in shear–dominated universe in section 3. In section 4, the constraints on the parameter space of shear–dominated universe are obtained using the observed Dark Matter relic density. The conclusion and summary are in the final section.

## 2 Review of the shear–dominated universe

In this section, we review the shear–dominated universe. In the standard cosmological scenario, it is assumed that the universe is isotropic and homogeneous. However before Big Bang Nucleosynthesis (BBN), there is no evidence which shows that the universe should be homogeneous or isotropic. One of the nonstandard cosmological scenarios is Bianchi type I model which is homogeneous but anisotropic cosmological model [11, 12, 13]. The expansion rate in this scenario is

$$H^2 = \frac{8\pi G}{3}(\rho_r + \rho_s), \quad (2)$$

where  $G = 1/(8\pi M_{\text{Pl}}^2)$  with  $M_{\text{Pl}} = 2.4 \times 10^{18}$  GeV,  $\rho_r = \pi^2 g_* T^4/30$  is the radiation energy density, here  $g_*$  is the effective number of the relativistic degrees of freedom.  $\rho_s$  is the shear energy density which is defined to be

$$\rho_s \equiv \frac{1}{48\pi G}[(H_1 - H_2)^2 + (H_1 - H_3)^2 + (H_2 - H_3)^2], \quad (3)$$

where  $H_i \equiv \dot{R}_i/R_i$  are the expansion rates for the three principal axes with  $R_i$  being the scale factors of the three principal axes of the universe. It is derived that shear energy density is proportional to  $\rho_s \propto \bar{R}^{-6}$  [14]. Here  $\bar{R}$  is the mean–scale factor as  $\bar{R} = V^{1/3}$  with  $V = R_1 R_2 R_3$ . We need explicit expression for the expansion rate to calculate the asymmetric Dark Matter relic density in this model. Using the conservation of the entropy per co–moving volume  $g_* \bar{R}^3 T^3 = \text{const}$ , the shear–energy density is expressed as  $\rho_s \propto g_*^2 T^6/\text{const}$ . It is defined at temperature  $T_e$ ,  $\rho_r = \rho_s$ . The universe is shear dominated when  $T \gg T_e$ , in which  $H \propto \bar{R}^{-3}$

and  $\bar{R} \propto t^{1/3}$ ; when the temperature falls well below  $T_e$  as  $T \ll T_e$ , the universe is radiation dominated, here the expansion rate  $H \propto \bar{R}^{-2}$  and  $\bar{R} \propto t^{1/2}$ . In terms of the radiation–energy density, the shear–energy density can be written as

$$\rho_s = \rho_r \left[ \frac{g_* T^2}{g_*^e T_e^2} \right], \quad (4)$$

where  $g_*^e$  is the value of  $g_*$  at  $T_e$ . The shear–energy density must be sufficiently small in order not to conflict with the successful prediction of BBN. BBN imposed the bounds on  $T_e \geq 2.5$  MeV. Then the total energy density in shear dominated universe is

$$\rho = \rho_r + \rho_s = \frac{\pi^2}{30} g_* T^4 \left[ 1 + \frac{g_* T^2}{g_*^e T_e^2} \right] \quad (5)$$

Finally the modified expansion rate is

$$H = \frac{\pi m_\chi^2}{M_{\text{Pl}} x^2} \sqrt{\frac{g_*}{90} \left( 1 + \frac{x_e^2}{x^2} \right)}, \quad (6)$$

where  $x = m_\chi/T$  with  $m_\chi$  being the mass of Dark Matter particles and the shear factor  $x_e$  is defined to be

$$x_e \equiv \frac{m_\chi}{T_e} \left[ \frac{g_*}{g_*^e} \right]^{1/2}. \quad (7)$$

### 3 Freeze–out of asymmetric Dark Matter in shear–dominated universe

The modified Hubble expansion rate has affects on the relic density of asymmetric Dark Matter in shear–dominated universe. In this section we investigate to what extent the relic density of asymmetric Dark Matter is affected if the asymmetric Dark Matter particles freeze–out in shear–dominated era. Dark Matter relic density is obtained by solving the following Boltzmann equations for particle and anti–particle which are written with the modified expansion rate as

$$\begin{aligned} \frac{dn_\chi}{dt} + 3Hn_\chi &= -\langle \sigma_{\chi\bar{\chi}} v \rangle (n_\chi n_{\bar{\chi}} - n_{\chi,\text{eq}} n_{\bar{\chi},\text{eq}}); \\ \frac{dn_{\bar{\chi}}}{dt} + 3Hn_{\bar{\chi}} &= -\langle \sigma_{\chi\bar{\chi}} v \rangle (n_\chi n_{\bar{\chi}} - n_{\chi,\text{eq}} n_{\bar{\chi},\text{eq}}), \end{aligned} \quad (8)$$

where  $\chi$  is the Dark Matter particle which is *not* self–conjugate, i.e. the anti–particle  $\bar{\chi} \neq \chi$ . In our work, we assumed that only  $\chi\bar{\chi}$  pairs can annihilate into Standard Model (SM) particles. Therefore  $\langle \sigma_{\chi\bar{\chi}} v \rangle$  is the thermal average of the cross section of the annihilating particles  $\chi$  and anti–particles  $\bar{\chi}$  multiplied with the velocity of the annihilating particles. Here  $n_\chi$  and

$n_{\bar{\chi}}$  are the number densities of particle and anti-particle and their equilibrium values are  $n_{\chi,\text{eq}} = g_{\chi} (m_{\chi}T/2\pi)^{3/2} e^{(-m_{\chi}+\mu_{\chi})/T}$  and  $n_{\bar{\chi},\text{eq}} = g_{\chi} (m_{\chi}T/2\pi)^{3/2} e^{(-m_{\chi}-\mu_{\bar{\chi}})/T}$ . Here we assume that the asymmetric Dark Matter particles were non-relativistic at decoupling.  $\mu_{\chi}$ ,  $\mu_{\bar{\chi}}$  are the chemical potential of the particle and anti-particle,  $\mu_{\bar{\chi}} = -\mu_{\chi}$  in equilibrium.

We follow the same method as in [6] and obtain the number densities for particle and anti-particle in shear-dominated universe. We assume the asymmetric Dark Matter particles  $\chi$  and  $\bar{\chi}$  were in thermal equilibrium when the temperature is high in the early universe. When  $T \leq m_{\chi}$ , the equilibrium values of the number densities  $n_{\chi,\text{eq}}$ ,  $n_{\bar{\chi},\text{eq}}$  decrease exponentially for  $m_{\chi} > |\mu_{\chi}|$ . Later the interaction rates for particle  $\Gamma = n_{\chi}\langle\sigma_{\chi\bar{\chi}}v\rangle$  and anti-particle  $\bar{\Gamma} = n_{\bar{\chi}}\langle\sigma_{\chi\bar{\chi}}v\rangle$  drop below the expansion rate  $H$ . This process leads to the decoupling of the particles and anti-particles from the thermal bath and the co-moving number densities are almost fixed from that inverse-scaled freeze-out temperature  $x_F$ .

The Boltzmann equations (8) can be rewritten in terms of the dimensionless quantities  $Y_{\chi} = n_{\chi}/s$ ,  $Y_{\bar{\chi}} = n_{\bar{\chi}}/s$  and  $x = m_{\chi}/T$ , where  $s = (2\pi^2/45)g_*T^3$  is the entropy density. Inserting Eq.(6) to the Boltzmann equations (8), then

$$\frac{dY_{\chi}}{dx} = -\frac{\lambda\langle\sigma_{\chi\bar{\chi}}v\rangle}{x\sqrt{x^2+x_e^2}} (Y_{\chi} Y_{\bar{\chi}} - Y_{\chi,\text{eq}} Y_{\bar{\chi},\text{eq}}); \quad (9)$$

$$\frac{dY_{\bar{\chi}}}{dx} = -\frac{\lambda\langle\sigma_{\chi\bar{\chi}}v\rangle}{x\sqrt{x^2+x_e^2}} (Y_{\chi} Y_{\bar{\chi}} - Y_{\chi,\text{eq}} Y_{\bar{\chi},\text{eq}}), \quad (10)$$

where  $\lambda = 1.32 m_{\chi} M_{\text{Pl}} \sqrt{g_*}$ . Combining these two equations (9), (10), we obtain

$$Y_{\chi} - Y_{\bar{\chi}} = \varepsilon, \quad (11)$$

here  $\varepsilon$  is constant. Then the Boltzmann equations (9) and (10) become

$$\frac{dY_{\chi}}{dx} = -\frac{\lambda\langle\sigma_{\chi\bar{\chi}}v\rangle}{x\sqrt{x^2+x_e^2}} (Y_{\chi}^2 - \varepsilon Y_{\chi} - P); \quad (12)$$

$$\frac{dY_{\bar{\chi}}}{dx} = -\frac{\lambda\langle\sigma_{\chi\bar{\chi}}v\rangle}{x\sqrt{x^2+x_e^2}} (Y_{\bar{\chi}}^2 + \varepsilon Y_{\bar{\chi}} - P), \quad (13)$$

where  $P$  is the product of  $Y_{\chi,\text{eq}}$  and  $Y_{\bar{\chi},\text{eq}}$ ,  $P = Y_{\chi,\text{eq}} Y_{\bar{\chi},\text{eq}} = (0.145 g_{\chi}/g_*)^2 x^3 e^{-2x}$ . To solve these Boltzmann equations (12) and (13), we use the annihilation cross section which is expanded in the relative velocity  $v$  of the annihilating Dark Matter particles, the thermal average is

$$\langle\sigma_{\chi\bar{\chi}}v\rangle = a + 6bx^{-1} + \mathcal{O}(x^{-2}), \quad (14)$$

where  $a$  is the  $s$  wave contribution to  $\sigma v$  when  $v \rightarrow 0$  and  $b$  is the  $p$ -wave contribution when  $s$ -wave annihilation is suppressed. Using the numerical solution of Eqs.(12), (13), we plot the evolution of  $Y_{\chi,\bar{\chi}}$  as a function of the inverse-scaled temperature  $x$  which is shown in

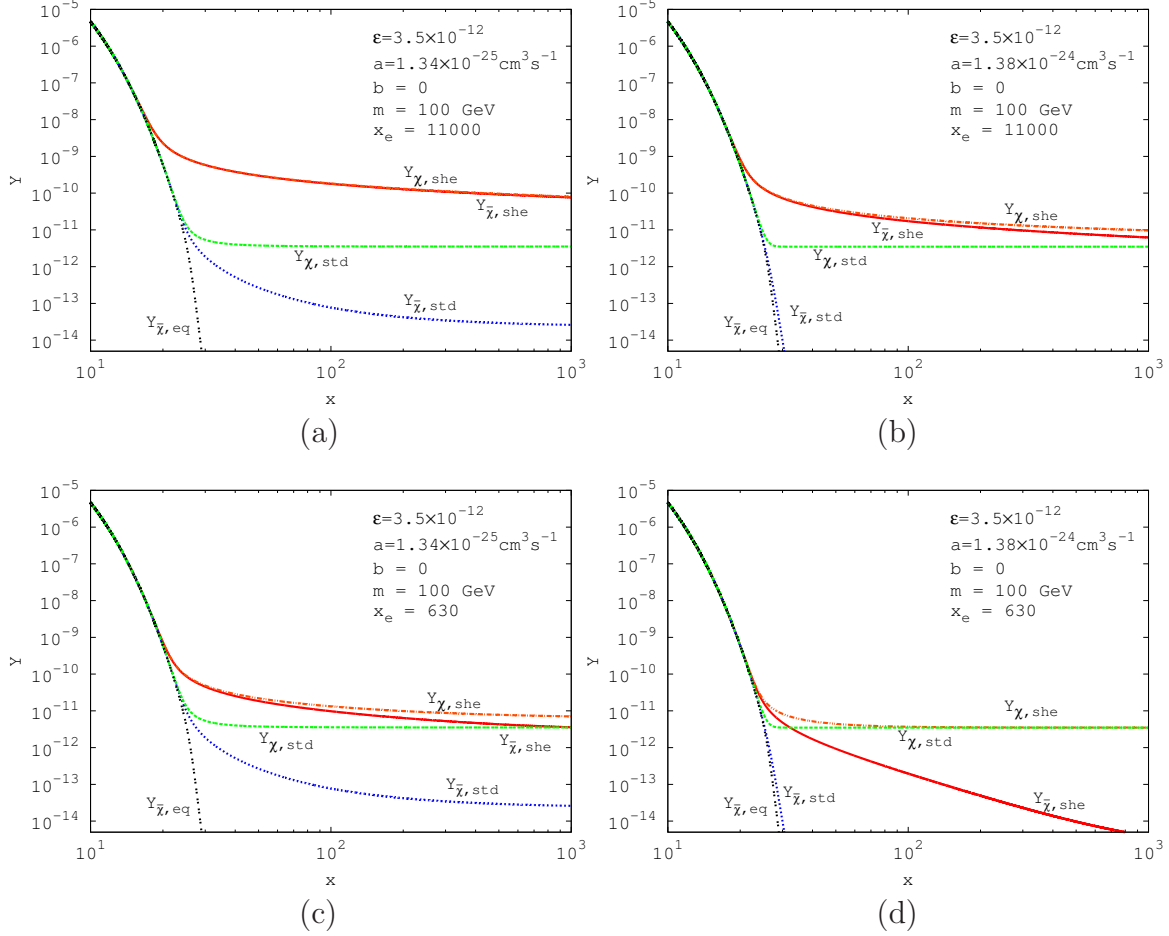


Figure 1: The relic abundances  $Y_\chi$  and  $Y_{\bar{\chi}}$  for particle and anti-particle in the standard and shear-dominated universe as a function of the inverse-scaled temperature  $x$  for  $\epsilon = 3.5 \times 10^{-12}$ ,  $m_\chi = 100 \text{ GeV}$ ,  $g_\chi = 2$ ,  $g_* = 90$ ,  $b = 0$ ,  $a = 1.34 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$  for (a) and (c),  $a = 1.38 \times 10^{-24} \text{ cm}^3 \text{ s}^{-1}$  for (b) and (d).  $x_e = 11000$  for panels (a), (b) and  $x_e = 630$  for panels (c) and (d).

Fig.1. The dot-dashed (red) line is the abundance  $Y_{\chi, \text{she}}$  for particle and thick (red) line is the abundance  $Y_{\bar{\chi}, \text{she}}$  for anti-particle in shear-dominated universe; the dashed (green) line is the abundance  $Y_{\chi, \text{std}}$  for particle and dotted (blue) line is the abundance  $Y_{\bar{\chi}, \text{std}}$  for anti-particle in the standard scenario. The double dotted (black) line is the equilibrium value of the anti-particle abundance  $Y_{\bar{\chi}, \text{eq}}$ . In this figure we can see how the shear increases the abundances of particle and anti-particle in the same time. For the same cross section and same asymmetry as in panels (a) and (c), the effect is more sizable for large  $x_e$ . Both the particle and anti-particle abundances are increased in the shear-dominated universe. We see that the particle and anti-particle decays earlier in shear-dominated model than the standard model, this leads to the increase of the abundances. The increase depends on the value of  $x_e$  for the same cross section. For example, the increase is larger for  $x_e = 11000$  in panel (a) comparing to the case in panel (c). For the same shear factor  $x_e$ , the increase is small for the larger annihilation

cross section in shear-dominated universe. It is shown in panels (a) and (b). For  $x_e = 630$ , the particle abundance in shear-dominated universe is almost same with the abundance in the standard cosmological scenario when the cross section is as large as  $a = 1.38 \times 10^{-24} \text{cm}^3 \text{s}^{-1}$ . We see that the anti-particle abundance is still suppressed for large annihilation cross section as in panel (d).

We can have the analytic solution of the relic density for asymmetric Dark Matter in shear-dominated model repeating the same method as in [6]. We only need to solve Eq.(13) for  $\bar{\chi}$  density. Later we can easily find  $Y_\chi$  using the relation  $Y_\chi - Y_{\bar{\chi}} = \varepsilon$ . In terms of  $\Delta_{\bar{\chi}} = Y_{\bar{\chi}} - Y_{\bar{\chi},\text{eq}}$ , the Boltzmann equation (13) is rewritten as

$$\frac{d\Delta_{\bar{\chi}}}{dx} = -\frac{dY_{\bar{\chi},\text{eq}}}{dx} - \frac{\lambda\langle\sigma_{\chi\bar{\chi}}v\rangle}{x\sqrt{x^2+x_e^2}} [\Delta_{\bar{\chi}}(\Delta_{\bar{\chi}} + 2Y_{\bar{\chi},\text{eq}}) + \varepsilon\Delta_{\bar{\chi}}] . \quad (15)$$

We get the solutions of this equation for two extreme cases: the solution for high temperature is

$$\Delta_{\bar{\chi}} \simeq \frac{2Px^2\sqrt{x^2+x_e^2}}{\lambda\langle\sigma_{\chi\bar{\chi}}v\rangle(\varepsilon^2+4P)} , \quad (16)$$

and for sufficiently low temperature i.e. for  $x > \bar{x}_F$ , Eq.(15) becomes

$$\frac{d\Delta_{\bar{\chi}}}{dx} = -\frac{\lambda\langle\sigma_{\chi\bar{\chi}}v\rangle}{x\sqrt{x^2+x_e^2}} (\Delta_{\bar{\chi}}^2 + \varepsilon\Delta_{\bar{\chi}}) . \quad (17)$$

We make the integration of Eq.(17) from  $\bar{x}_F$  to  $\infty$  and obtain the final WIMP abundance for anti-particles. The integration range includes two parts: one is from  $\bar{x}_F$  to  $x_e$  where the shear-dominated cosmology is used; The second part is from  $x_e$  to  $\infty$  where the standard cosmology is recovered. Then we obtain

$$Y_{\bar{\chi}}(x \rightarrow \infty) = \frac{\varepsilon}{\exp[1.32\varepsilon m_\chi M_{\text{Pl}} \sqrt{g_*} I(\bar{x}_F, x_e)] - 1} , \quad (18)$$

where

$$\begin{aligned} I(\bar{x}_F, x_e) &= \int_{\bar{x}_F}^{x_e} \frac{\langle\sigma_{\chi\bar{\chi}}v\rangle}{x\sqrt{x^2+x_e^2}} dx + \int_{x_e}^{\infty} \frac{\langle\sigma_{\chi\bar{\chi}}v\rangle}{x^2} dx \\ &= \frac{a}{x_e} \ln \left[ \frac{x_e}{(1+\sqrt{2})\bar{x}_F} \left( 1 + \sqrt{1 + \left(\frac{\bar{x}_F}{x_e}\right)^2} \right) \right] \\ &\quad + \frac{6b}{x_e^2} \left[ -\sqrt{2} + \sqrt{1 + \left(\frac{x_e}{\bar{x}_F}\right)^2} \right] + \frac{a}{x_e} + \frac{3b}{x_e^2} . \end{aligned} \quad (19)$$

Then the relic abundance for  $\chi$  particle is

$$Y_\chi(x \rightarrow \infty) = \frac{\varepsilon}{1 - \exp[-1.32\varepsilon m_\chi M_{\text{Pl}} \sqrt{g_*} I(x_F, x_e)]} , \quad (20)$$

here  $I(x_F, x_e)$  is same as Eq.(19) with the substitution of  $\bar{x}_F$  to  $x_F$ . The two Eqs.(18) and (20) are consistent with Eq.(11) if  $x_F = \bar{x}_F$ . In terms of the critical density  $\rho_{\text{crit}} = 3M_{\text{Pl}}^2 H_0^2$ , the final abundance is expressed as

$$\Omega_{\text{DM}} h^2 = \frac{m_\chi s_0 [Y_\chi (x \rightarrow \infty) + Y_{\bar{\chi}} (x \rightarrow \infty)] h^2}{\rho_{\text{crit}}}, \quad (21)$$

where  $s_0 = 2.9 \times 10^3 \text{ cm}^{-3}$  is the present entropy density. The predicted present relic density for Dark Matter is then given by

$$\Omega_{\text{DM}} h^2 = \frac{2.76 \times 10^8 \varepsilon m_\chi}{1 - \exp [-1.32 \varepsilon m_\chi M_{\text{Pl}} \sqrt{g_*} I(x_F, x_e)]} - \frac{2.76 \times 10^8 \varepsilon m_\chi}{1 - \exp [1.32 \varepsilon m_\chi M_{\text{Pl}} \sqrt{g_*} I(\bar{x}_F, x_e)]}. \quad (22)$$

The freeze-out temperature for  $\bar{\chi}$  is fixed by assuming that the deviation  $\Delta_{\bar{\chi}}$  is of the same order of the equilibrium value of  $Y_{\bar{\chi}}$ :

$$\xi Y_{\bar{\chi}, \text{eq}}(\bar{x}_F) = \Delta_{\bar{\chi}}(\bar{x}_F), \quad (23)$$

with  $\xi$  being the numerical constant of order unity. We choose the usual value  $\xi = \sqrt{2} - 1$  [16]. The obtained approximate analytic result matches with the exact numerical result well within 5% for all combinations of parameters.

## 4 Constraints on parameter space

We use the data in Eq.(1) which is given by Planck [2] to find the constraints on the parameter space in shear-dominated universe for asymmetric Dark Matter. Fig.2 shows the relation between the cross section parameter  $a$  and asymmetry factor  $\varepsilon$  for the shear-dominated universe and standard cosmology when the Dark Matter relic density  $\Omega_{\text{DM}} h^2 = 0.1199$ . The cross section for shear-dominated model is larger than the standard cosmological model. This is similar to the other non-standard cosmological models [7, 8, 9, 10]. For larger  $x_e$ , one needs larger annihilation cross section. Indeed this can be understood from Fig.1. For larger  $x_e$ , the particle and anti-particle decay more earlier than the case for smaller  $x_e$  and it results larger relic density. If one wants to satisfy the observation range, the cross section must be large. In Fig.2, i.e. when  $\varepsilon = 1 \times 10^{-13}$ , the s-wave annihilation cross section  $a = 3.99 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$  for the standard cosmology which corresponds to the case  $x_e = 0$  and it is increased to  $a = 8.82 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$  for  $x_e = 130$ ;  $a = 4.66 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$  for  $x_e = 1300$ ;  $a = 1.93 \times 10^{-24} \text{ cm}^3 \text{ s}^{-1}$  for  $x_e = 7300$ .

As we mentioned in the introduction, for asymmetric Dark Matter, in the beginning, it is assumed there is less anti-particle than the particle and the anti-particle is completely annihilated away with the particle at late time and there are only particles which made up



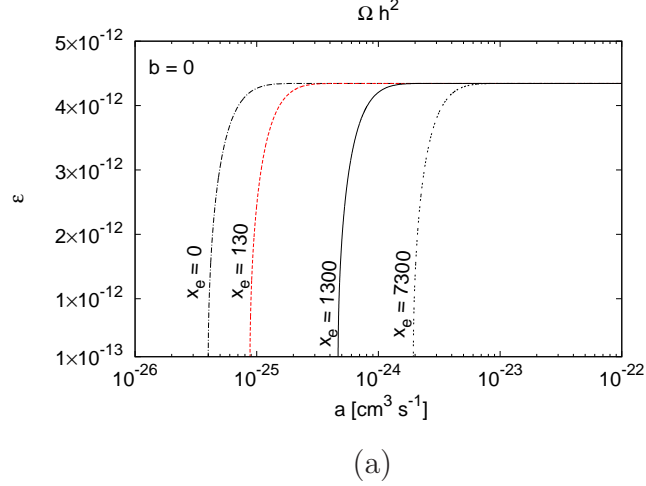


Figure 2: The allowed region in the  $(a, \varepsilon)$  plane for different  $x_e$  when  $b = 0$  and the Dark Matter relic density  $\Omega_{\text{DM}} h^2 = 0.1199$ . Here we take  $m_\chi = 100$  GeV,  $g_\chi = 2$  and  $g_* = 90$ . The dot-dashed line is for standard cosmology where  $x_e = 0$  and the dashed (red) line is for  $x_e = 130$ , the thick line for  $x_e = 1300$  and the double-dotted line for  $x_e = 7300$ .

the present total Dark Matter abundance in the standard cosmological scenario. Therefore, the asymmetric Dark Matter particle is supposed to be detected by direct detection and the indirect detection is not possible for the asymmetric Dark Matter. However, it is different in nonstandard cosmological scenarios. The increase of the annihilation cross section leads to the increase of the annihilation rate. The increased annihilation rate for particle and anti-particle gives the possibility to detect the asymmetric Dark Matter in indirect way. It is derived in Ref.[7], the ratio of the annihilation rate for asymmetric Dark Matter and symmetric Dark Matter is less than 1,

$$\frac{\Gamma_{\text{asym}}}{\Gamma_{\text{Fermi}}} = \frac{\langle \sigma_{\chi\bar{\chi}} v \rangle}{\langle \sigma v \rangle_{\text{Fermi}}} \frac{2Y_\chi Y_{\bar{\chi}}}{(Y_\chi + Y_{\bar{\chi}})^2} < 1, \quad (24)$$

Using Eq.(22), we obtain

$$\frac{\Omega_{\text{DM}} h^2}{2.76 \times 10^8 m_\chi} \left( 1 - 2 \frac{\langle \sigma v \rangle_{\text{Fermi}}}{\langle \sigma_{\chi\bar{\chi}} v \rangle} \right)^{1/2} < \varepsilon. \quad (25)$$

Fermi Large Area Telescope (Fermi-LAT) gives the upper bounds [17]  $a = 1.34 \times 10^{-25} \text{cm}^3 \text{s}^{-1}$  for  $\chi\bar{\chi} \rightarrow b\bar{b}$  and  $a = 1.38 \times 10^{-24} \text{cm}^3 \text{s}^{-1}$  for  $\chi\bar{\chi} \rightarrow \mu^\dagger \mu^-$  for  $m_\chi = 100$  GeV. Applying Planck data and Fermi-LAT data to Eq.(25), we plot the limiting cross sections in shear-dominated model. The thick line is for  $\chi\bar{\chi} \rightarrow b\bar{b}$  and double-dotted line is for  $\chi\bar{\chi} \rightarrow \mu^\dagger \mu^-$  in Fig.3. For the smaller asymmetry factor, i.e.  $\varepsilon = 1 \times 10^{-13}$ , the corresponding limiting cross sections are  $\langle \sigma v \rangle_{\chi\bar{\chi}} \leq 2.68 \times 10^{-25}$  for  $\chi\bar{\chi} \rightarrow b\bar{b}$  and  $\langle \sigma v \rangle_{\chi\bar{\chi}} = 2.76 \times 10^{-24}$  for  $\chi\bar{\chi} \rightarrow \mu^\dagger \mu^-$ . For larger  $\varepsilon$ , i.e.  $\varepsilon = 3.5 \times 10^{-12}$ , the corresponding limiting cross sections are  $\langle \sigma v \rangle_{\chi\bar{\chi}} \leq 7.67 \times 10^{-25}$  for  $\chi\bar{\chi} \rightarrow b\bar{b}$  and  $\langle \sigma v \rangle_{\chi\bar{\chi}} = 7.90 \times 10^{-24}$  for  $\chi\bar{\chi} \rightarrow \mu^\dagger \mu^-$ . The corresponding shear factor  $x_e$  to

the maximum annihilation cross section must be 639 for  $\chi\bar{\chi} \rightarrow b\bar{b}$  and 11060 for  $\chi\bar{\chi} \rightarrow \mu^\dagger\mu^-$  in shear-dominated universe.

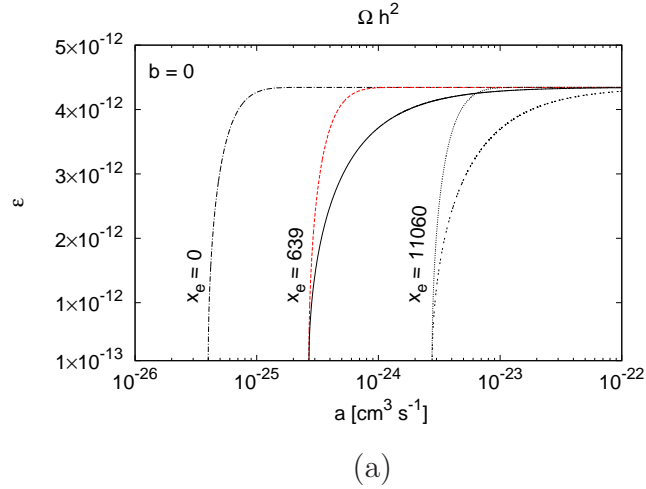


Figure 3: The parameters are same as in Fig.2 with the two lines without label are the limiting cross sections which corresponds to the Fermi-LAT bounds [17] where the thick line is for  $\chi\bar{\chi} \rightarrow b\bar{b}$  and the double-dotted line is for  $\chi\bar{\chi} \rightarrow \mu^\dagger\mu^-$ ; the dashed (red) line is for  $x_e = 639$  and the dotted line is for  $x_e = 11060$ . The dot-dashed line is for standard cosmology.

However, for smaller value of  $x_e$ , when the cross section is large, the anti-particle abundance is still suppressed as shown in plot (d) in Fig.1. At finally, there is particle only. Therefore, whether we can use the indirect detection signal for asymmetric Dark Matter in shear-dominated universe depends on the value of the shear factor  $x_e$  and the annihilation cross section.

## 5 Summary and Conclusions

In this paper, we investigated the relic abundance of asymmetric Dark Matter which decouples from the thermal equilibrium during the nonstandard cosmological phase. We focus on the Bianchi type I model which assumes the universe is expanded anisotropically before BBN. If the freeze-out occurs in the shear-dominated era, then the relic abundances of asymmetric Dark Matter particle and anti-particle are affected. The Hubble rate is larger in shear-dominated universe than the standard radiation-dominated cosmological model. This leads to the early decay of the asymmetric Dark Matter particles. As a result, the relic abundances of Dark Matter particles increase. We found that the relic densities of both particles and anti-particles are increased in shear-dominated universe. The size of the increase depends on the value of the shear factor  $x_e$  and the annihilation cross sections. For the same cross section, the increases are more sizable for larger  $x_e$ .

We used the Planck data to find the constraints on the annihilation cross section and asymmetry factor  $\varepsilon$  in shear-dominated model. The cross section is increased for shear-dominated universe comparing to the standard cosmology. For large  $x_e$ , the cross section should be large enough in order to let the Dark Matter abundance falls in the observation range. We showed that the indirect detection signal is possible for asymmetric Dark Matter in shear-dominated universe for appropriate  $x_e$  value.

If we know the annihilation cross section of the asymmetric Dark Matter candidates and the annihilation rate is detectable at present, we can test the universe before Big Bang Nucleosynthesis. Therefore, it is useful to investigate the early universe before BBN.

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